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RESEARCH ARTICLE

Evaluating design parameters for improved efficiency in solar-powered air cooling systems for cold storage warehouses

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Abstract

Solar energy has strong potential to power cooling systems in cold-storage facilities; however, the impact of varying design parameters on system efficiency remains underexplored. This study aims to evaluate the effect of various design parameters on the performance of a solar-operated air-cooling system for cold storage applications. A comprehensive approach was used to analyze the influence of solar panel orientation, cooling system configuration, thermal storage, and insulation characteristics. To develop a performance-optimization model considering solar collector type, airflow rate, and cooling load requirements, real-time data were analyzed throughout the study. Experimental trials showed that through design optimization, the efficiency of the system could be considerably enhanced, and energy savings were increased. The solar absorption cooling system provided airflow rates ranging from 400 m^3/h in the morning to a maximum of 550 m^3/h at noon, decreasing to 450 m^3/h in the afternoon. The results indicate that a combined design optimization approach enables improvement in the performance of the solar cooling system in cold-storage applications. This approach helps reduce energy dependence while maintaining consistent cooling performance.

Keywords: Air cooling systems, cold storages, warehouses, green energy

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1. Introduction

The cold storage warehouse plays a very important role in the maintenance of perishable goods quality by creating a controlled environment. However, conventional cooling systems in the cold storage warehouse depend on energy sources that increase operational costs and contribute to environmental degradation. Solar energy is renewable and freely available, hence providing opportunities for reduced dependence on fossil fuels, reducing thereby the carbon footprint from such facilities [1], [2]. It seeks to identify the most influential design parameters affecting the performance of solar-operated, air-cooled cold storage warehouses and to optimize them. The main aim is the development of a highly efficient system with full assurance of cost-effectiveness and reliability [1].

Cold storage houses play an important role in the global supply chain, maintaining perishable items such as fruits, vegetables, and dairy products, as well as pharmaceuticals [3]. Major efficiency in such warehouses depends on the cooling systems, which maintain a particular temperature and humidity so that items will not spoil [4]. Conventional cooling systems are usually operated on electricity generated from fossil fuel, which is costly and has many environmental hazards associated with it, especially greenhouse gases [5].

This has increased public interest in using renewable energy sources to power cold storage systems amid concerns about energy sustainability and environmental impact. Solar energy, especially in regions with abundant sunlight, is considered a viable alternative owing to its abundance. Given that solar air-cooling systems have more advantages compared to conventional systems-including reduced dependence on fossil fuel and reducing operational costs-they still hold promise for cold storage applications [6]. In solar-powered air cooling, however, performance depends on several design parameters, such

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as collector type, cooling load, airflow rate, and insulation quality. Despite these advantages, widespread diffusion of solar-powered cooling systems in cold storage warehouses remains limited, partly because few studies have evaluated their performance across variable design parameters. In fact, a clear understanding of the influence of these parameters on system efficiency is essential for the optimization of design and effective functioning [7], [8].

The present research responds to this need by exploring basic design parameters that influence the efficiency of solar-powered air-cooling systems in cold-storage warehouses. The work involves experimental and simulation studies with a view to arriving at optimal design configuration that maximizes cooling efficiency with a minimum of energy use [9]. Cold storage facilities are essential for maintaining the freshness of perishables but rely primarily on cooling systems. There is strong potential for solar energy to replace such systems that may be in areas receiving high solar irradiance. The effect of changing parameters affecting efficiency has been less explored. Here, a study has been undertaken to investigate how different design parameters affect the performance of a solar-operated air-cooling system for the cold storage facility. The results of this work will provide useful guidelines for the design and installation of solar-powered cooling applications, thereby helping develop cold storage solutions that are more economically and environmentally viable. The next sections discuss the related literature on the subject, then go on to describe the methodology for the study of the design parameters, after which results of the studies are presented and discussed in relation to implications for the industry [10].

2. Related work

Solar energy applications in cooling systems have attracted keen interest in recent years. Different studies have considered various application contexts for solar-powered cooling systems, ranging from residential and commercial to industrial settings. Little or no research can be found regarding what particularly concerns the needs and problems of cold storage warehouses [11]. Critical design parameters include the orientation and type of solar collectors, the selection of refrigerant, and the design of the airflow system. Indeed, this review underlines a holistic analysis required towards these parameters for optimally building the performance of solar-operated cooling systems in the cold storage environment [12].

Increased demand for sustainable energy has encouraged extensive research into employing solar energy for cooling applications, particularly for cold-storage warehouses. The review covers the literature on solar-powered cooling technologies, identifies the key design parameters, and points out the gaps that this research aims to address. Solar energy, being renewable and sustainable, has increasingly been incorporated into various cooling applications. The study, however, emphasized that performance was variable with respect to specific solar technologies and application cooling requirements. Solar energy-driven air-cooling systems are promising for maintaining a controlled atmosphere inside cold storage facilities. Kumar (2018) studied various solar cooling technologies, such as photovoltaic and solar thermal systems. Research by two researchers showed that PV-based systems were more appropriate for smaller applications but unsuitable for large-scale cold storage, whereas solar thermal systems using absorption refrigeration were more suitable because they were more efficient in converting solar energy into cooling power. To this regard, matching of cooling load with the capacity of the system for maximum performance was pointed out by the study [13]. Efficiency and effectiveness in solar-powered air-cooling systems depend on various design parameters. First, there's the choice of solar collectors [14].

According to Duffie and Beckman, there are three main kinds of solar collectors: flat-plate collectors, evacuated tube collectors, and concentrating collectors. Among these, evacuated tube collectors are generally more efficient at capturing incident energy, especially in colder climates, and thus could be superior for a solar-powered cooling system. Cooling load, defined mainly by the size of the warehouse, insulation, and intensity of the external temperature, is an important factor in system design [2]. Alajmi et al. (2020) introduce accurate cooling load calculation as the basis upon which one can ensure that the system is neither under-sized-in which case inefficiency ensues-nor over-sized, with its consumption of more energy than necessary. Proper distribution of airflow is of vital importance for the maintenance of uniform temperatures in the storage space [15]. Wang et al. revealed that the energy efficiency and cooling ability of the system have significant dependence on the different airflow rates. Their study suggested that they need to optimize airflow rates to ensure adequate temperature control while minimizing energy consumption. Insulation plays an important role in reducing the transfer of heat from outside environment [16].

Tian and Zhao (2015) demonstrated that good insulation materials can reduce cooling loads to a minimum, hence increasing the overall efficiency of the systems. The authors identified that an initial investment in improved insulation can be offset by long-term energy savings. Although research on solar cooling systems has been conducted, few studies have comprehensively assessed how different design parameters influence the performance of solar-powered air-cooling systems applied exclusively to cold-storage warehouses. In addition, most research has been focused on residential and commercial applications, while limited attention has been directed to specific settings such as cold storage facilities. Also, further experimental studies were conducted to validate simulation models with real conditions, especially under varying climatic conditions [17].

3. Methodology

3.1. System design and configuration

The study introduced a solar-powered air-cooling system for a cold-storage warehouse. It consists of solar collectors, a heat exchanger, refrigerant pipes, and an airflow distribution network. Several major design parameters were investigated to optimize the performance of a solar-operated air-cooling system for cold storage warehouses of all considerations, one of the most critical aspects is the kind of solar collector [18]. Flat-plate Collectors, evacuated-tube collectors, and parabolic-trough collectors were the varieties studied. Each type of collector has its own advantages and disadvantages. Therefore, performance ratings had to be obtained for each of them under different operating conditions to identify the best option for this application. Another important design consideration was the cooling load calculation. The calculation was based on the size of the warehouse, the nature of goods in storage, and the ambient temperature. Knowledge of the cooling load would be beneficial for the design of the cooling system to ensure it can meet the required temperature and maintain the stored goods in optimal condition. The cooling performance and temperature distribution in the warehouse under different airflow rates were also analyzed. The airflow rate was an important consideration to ensure that cool air was delivered uniformly to the storage area, preventing hot spots and maintaining a consistent temperature. Finally, insulation quality was studied in detail; it served to minimize heat gain from the outside, thereby reducing the overall cooling load and maintaining a relatively stable internal temperature. The study underlined that high-quality insulation significantly improves the efficiency of the cooling system and makes it possible for the operation to be effective over time [19].

3.2. Experimental setup

The installation location was chosen to maximize exposure to solar irradiance and thereby achieve greater efficiency of the solar collectors. Jalgaon, located in the state of Maharashtra, India, lies at latitude 21.0077° North and longitude 75.5626° East. The system is installed in a prototype cold-storage warehouse, and sensors measuring temperature, humidity, and airflow are placed at appropriate points. Testing and data collection are carried out under various working conditions, including ambient temperature, load, and solar intensity. The Zonen CMP series was used to measure the global solar irradiation (W/m²) on a flat surface with a pyranometer. It can convert sunlight into an electrical signal proportional to the incident solar radiation. The ambient air surrounding the sensor was precisely measured using a digital temperature sensor. Internal load conditions are monitored using temperature sensors (RTDs) to measure internal temperature and airflow sensors (hot-wire anemometers) to measure ventilation rate. In addition, power consumption is measured using CT and Hall-effect sensors to estimate the electrical load. Solar irradiance sensors (pyranometers) are very sensitive and are installed on rooftops or tilted with the panels. Ambient temperature sensors are in shady outdoor locations to within ±0.5°C. Cold storage is equipped with an energy meter to record energy consumption, temperature sensors to ensure that the cold storage maintains its cold temperature, and air flow sensors to monitor air flow in the ducts. All sensors provided high sensitivity, resulting in high measurement accuracy.

This design is ideal for promoting energy efficiency and temperature stability in cold storage warehouses by combining solar power with modern cooling systems. Solar collectors attached to the roof of the warehouse convert sun rays into heat energy [20]. These are then connected to the heat exchanger with insulated pipes to reduce energy losses and improve efficiency. It therefore plays an important role in transferring the heat absorbed by the solar collectors to the refrigerant in the cooling system. It therefore reduces the energy required to maintain low temperatures in the warehouse. This cooling medium is distributed within the facility by refrigerant pipes that connect the heat exchanger to the cooling units. Insulating these pipes reduces energy loss, thereby enabling the refrigerant to absorb more heat from inside the warehouse and release it outside efficiently. Complementing this process is an airflow distribution system that delivers cool air uniformly throughout the storage area. This system is designed to distribute and circulate air and to ensure that the temperature remains consistent throughout the storage area, thereby preventing temperature fluctuations that could damage the stored items. The combination of solar energy, the refrigerant network and the airflow results in an energy efficient and sustainable climate in cold storage buildings [21]. Figure 1 highlights the condenser's internal storage unit and external unit used in the setup.

Figure 1. (A) Internal storage unit and **(B)** External unit of condenser used in setup

3.3. Performance metrics

Performance metrics are based on cooling efficiency, energy consumption, and the effectiveness of system-reliability tests. The system's ability to maintain the desired internal temperature reflects cooling efficiency, while the total amount of energy used quantifies the system's energy consumption. System reliability refers to the consistency of performance over time and under varying conditions. The data collected is analyzed using statistical methods to determine the impact of each design parameter on system performance [22].

4. Results and discussion

4.1. Influence of design parameters

On the other hand, the analysis indicates that the type of solar collector significantly affects system efficiency, especially evacuated tube collectors, which achieve the highest efficiency under the same conditions. Calculations of cooling loads have shown that properly determining a warehouse's cooling load, in terms of size and contents, is key to correct system design. In addition, adjustments to the airflow rate affect the temperature distribution: higher rates produce more homogeneous cooling but increase energy consumption. Insulation quality is a major factor in maintaining internal temperature and reducing energy loss. The following design factors directly affect energy efficiency, temperature control, and overall sustainability of the cold storage system, on which much of its success depends. Among these several factors are the orientation and effectiveness of the solar collectors, the type of heat exchanger design, the insulation at the refrigerant pipes, and the network configuration for airflow distribution as shown in Figure. 2 [23]. Table 1 highlights the influence of design parameters on the efficiency of solar-powered cooling systems.

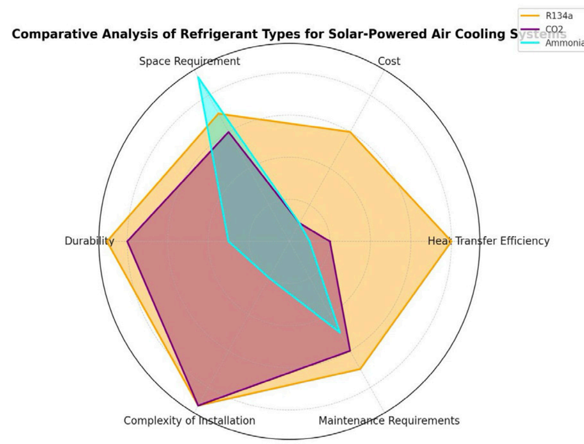

Figure 2. Comparative analysis of refrigerant types for solar-powered air-cooling system

Table 1. Influence of design parameters on efficiency in solar-powered cooling systems

DesignParameter	Variable	Impact on Efficiency	Observation/Expected Outcome
Solar Collector Placement	Position (Angle, Orientation)	Affects solar energy absorption	Optimal placement increases energy capture by up to 25%
Solar Collector Size	Surface Area (m^2)	Impacts energy availability for cooling	Larger collectors improve cooling but may have diminishing returns
Heat Exchanger Type	Shell-and-tube, Plate, Finned	Efficiency of heat transfer	Shell-and-tube type provides 15% more heat transfer efficiency
Heat Exchanger Surface Area	Size (m^2)	Increases the rate of thermal energy transfer	Larger surface area improves efficiency but increases costs
Refrigerant Pipe Insulation	Material, Thickness	Minimizes heat gain during refrigerant transfer	2x thicker insulation reduces energy losses by 20%
Refrigerant Pipe Length	Total length of piping system (meters)	Longer pipes cause pressure drops and energy losses	Shorter pipe networks reduce refrigerant energy loss by 10%
Airflow Network Design	Duct Layout and Fan Placement	Affects distribution of cool air within storage areas	Optimized layouts prevent hotspots and maintain uniform cooling
Fan Speed Control	Use of Variable Frequency Drives (VFD)	Optimizes energy usage based on real-time cooling demand	VFD-controlled fans reduce energy consumption by 15%-20%
Duct Material	Material Type (Steel, Aluminum)	Impacts air resistance and energy efficiency	Lower resistance materials increase airflow efficiency by 10%
Cooling Load	Temperature requirements, Volume	Influences energy demand and system capacity	Higher cooling loads require more efficient design to minimize energy consumption

In Table 2, the energy performance of the solar collector system depends on the positioning and efficiency of the solar collectors. It can be optimally positioned on the roof to capture maximum sunlight, thereby improving system efficiency by enhancing the conversion of sunlight into thermal energy. The Sizing and number of solar panels need to be determined, because the system may not be able to meet peak cooling demands if it is undersized and may waste energy if it is oversized. The form of the collector (the tilt and the material it is made with) also affects the amount of heat that will be collected.

Table 2. Design criteria and their impact on system

Design Parameter	Variable	Impact on System	Effect on Performance	Additional Notes
Material Selection	Steel, Aluminum, Composite	Impacts structural strength and durability	Higher strength-to-weight ratio improves efficiency	Choice depends on application (e.g., structural vs. thermal)
Component Size	Small, Medium, Large	Influences system scalability and capacity	Larger size may increase capacity but decrease efficiency	Size optimization is critical to avoid over/under-sizing
Shape & Geometry	Circular, Rectangular, Irregular	Affects airflow, stress distribution, and therma flow	More aerodynamic shapes improve flow and reduce losses	Complex geometries may be difficult to manufacture
Surface Finish	Smooth, Textured, Coated	Impacts friction, heat transfer, and corrosion resistance	Smooth surfaces reduce drag and energy loss	Coatings may improve longevity but add cost
Energy Source Configuration	Solar, Electric, Hybrid	Alters energy consumption and system	Renewable sources reduce operational costs	Requires evaluation of cost-benefit over time
Insulation Type	Foam, Fiberglass, Vacuum	Determines thermal efficiency	Improved insulation reduces energy loss	Balance between cost and insulation effectiveness
Operating Temperature	Low, Medium, High	Affects material choice and cooling efficiency	Higher temperatures require materials with better thermal properties	May increase system complexity
Fan Speed	Variable, Fixed	Alters airflow control and power usage	Variable speed increases adaptability and efficiency	Controlled by automated systems to optimize performance
Control System Type	Manual, Semi-Automatic, Automatic	Impacts ease of use, precision, and energy savings	Automatic systems reduce human error and improve efficiency	Automation increases upfront cost but offers long-term gains

The design of the heat exchanger is crucial, as it determines how effectively the energy collected by the solar panels is transferred to the refrigerant. An efficient heat exchanger minimizes energy loss during the transfer process, thereby producing a greater cooling effect. The overall size, surface area, and configuration determine how well it performs. If the heat exchanger is poorly designed, it increases the cooling system's energy consumption, thereby undermining some of the benefits of solar power. Another very important parameter to save energy is the insulation of refrigerant pipes [25]. Good insulation will avoid the heat gain in the flow of the refrigerant in its path through the system. In the absence of adequate insulation, the refrigerant is heated before reaching the cooling units, thereby increasing the energy required to cool it again. To minimize heat loss and prevent pressure drops within the system, the material, thickness, and placement of the insulation and to the length and arrangement of the pipes. The degree of cooling within the storage depends on the design of the airflow network. The main problems are the placement of the duct, the number of fans and the rate of air flow. Inadequate network design can result in unequal cooling, which can cause temperature variations that can impact product quality. To design airflow effectively, fans and ducts should be strategically placed to ensure even distribution of cool air. The speed of the fans can also be adjusted according to the actual temperature data, which can optimize performance, and reduce the energy consumption [26].

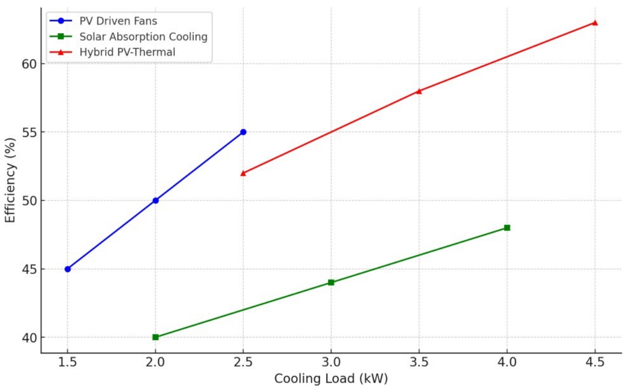

Figure 3. Cooling load vs efficiency for solar-power air cooling system

The efficiency of three different solar air-cooling systems, such as the PV fans, solar absorption cooling systems and hybrid PV-thermal systems, is analyzed at various cooling loads in kilowatts (kW) as shown in Figure. 3. The x-axis represents the cooling load (1.5 kW to 4.5 kW); the y-axis represents system efficiency (in percent). The performance trend varies across systems for a given cooling load.

The general energy balance for a flat-plate collector can be expressed as:

Q_collected = A * I * η_collector * (T_collector - T_ambient) (1)

η_thermal = Q_useful / Q_incident (2)

Q_HTF = m * C_p * (T_out - T_in) (3)

Q = Q_internal + Q_external + Q_ventilation (4)

COP = Q_cooling / P_input (5)

The PV-driven fans (blue line) exhibit a steady increase in efficiency with increasing cooling loads. For instance, at a cooling load of 1.5 kW, the system efficiency is around 45%, increasing to about 55% at 2.5 kW. Although efficiency exhibits an upward trend, the system appears to operate most efficiently within a narrow range of lower cooling loads. Therefore, PV-driven fans could prove useful for small-scale applications or where moderate cooling demands apply. Of the three, the solar absorption system with the lowest practical efficiency is represented by the green line; at a cooling load of 2 kW, it operates at around 40% efficiency. It achieves an efficiency of approximately 45% at a cooling load of 4 kW. This moderate growth rate indicates that solar absorption cooling is less responsive to escalating cooling loads and is incapable of providing high performance. However, its small efficiency increase suggests that it might be more appropriate for use in applications where cooling requirements do not fluctuate and are moderate. The system with PV-thermal, indicated by the red line, always has the highest efficiency across all cooling loads. It starts at about 50% efficiency at a cooling load of 2.5 kW and increases steadily to about 65% at 4.5 kW. This means that the system can be adapted well to sustain increased cooling requirements. For high-demand cooling applications and large-scale use, the hybrid PV-thermal system is the most efficient and versatile solution for utilizing both PV and thermal energy. The efficiency of these hybrid systems varies considerably across different cooling loads. Under high loads, hybrid PV-thermal systems can achieve the greatest efficiency improvements. The greatest improvement in efficiency is achieved with hybrid PV-thermal technology, particularly under higher loads. For smaller cooling loads, PV-driven fans produce moderate improvements, while solar absorption cooling ranks lowest and is therefore less promising for high-performance applications.

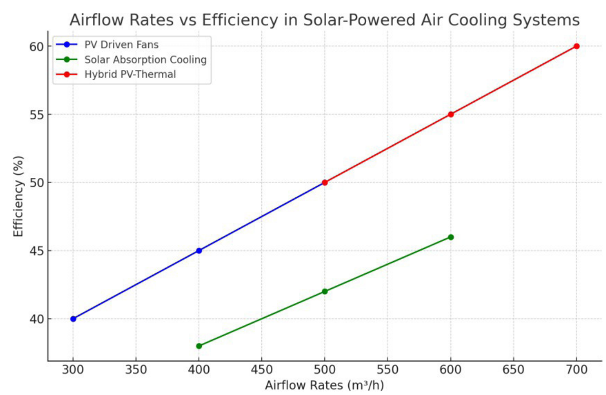

Figure 4. Airflow rates vs efficiency in solar-powered air-cooling systems

Figure 4 shows the efficiency of three solar-powered air-cooling systems as a function of airflow rate. The rates are in cubic meters per hour (m^3/h). The efficiency is given as a percentage, and the mass flow rate (x-axis) is between 300 m^3/h and 700 m^3/h. At these different airflow rates, different trends of system are observed as it becomes more efficient. The blue line in the graph represents PV-driven fans, which exhibit a linear relationship with airflow rates and a high coefficient of determination. The system would start with an efficiency slightly above 40% at a flow rate of 300 m^3/h. A higher airflow rate of 500 m^3/h increased efficiency to just over 50%. This near linear growth suggests PV-driven fans gain significant advantages at higher airflow and is deemed reliable in a moderate air flow range. Their operating range, however, seems relatively modest compared with the operating ranges of other systems, making them more appropriate for small-scale applications or for conditions of moderate airflow demand.

The greenish color of the solar absorption cooling system indicates an initial efficiency of about 40% at 400 m^3/h, increasing to approximately 45% at 600 m^3/h. Compared with the other three systems, the gain in efficiency with increasing airflow is slightly smaller. This suggests that solar absorption cooling systems are less sensitive to increases in airflow rate, possibly because their thermal energy conversion processes require a minimum level of thermal input. Their performance is also limited to a narrower range of airflow than that of others, possibly implying that it is best suited to applications requiring steady, moderate airflow. The hybrid PV-thermal system, shown by the red line, outperforms the two other systems at all observed airflow rates.

The efficiency of the system also improves, reaching a maximum of around 60% at 700 m^3/h, compared with around 50% at 500 m^3/h. The result indicates that the greater the airflow, the more the hybrid system can utilize PV and thermal energy. It is the most effective system for applications with higher air flow rates or where maximum efficiency is desired and is scalable and adaptable to a wide range of applications. The efficiencies of these three systems are affected by flow rates, as shown in the figure. HPT systems always have high efficiency and are appropriate for high flow rates. PV-powered fans provide moderate efficiency improvements but are limited to low-demand applications. However, the smallest improvement in efficiency was observed in the solar absorption cooling system. This reduces the system's applicability to applications that require variable airflow. Such findings are an indication that the system needs to be matched to the requirements of the application in terms of airflow [2].

Comparison with existing systems

A comparison is made between the performance of the solar-operated air-cooling system and traditional cooling systems typically used in cold-storage warehouses. These results show that the solar-operated system can achieve comparable cooling efficiency with significantly lower energy consumption, especially when design parameters are optimized, as given in Table 3.

Table 3. Design parameters with numerous conditions and their impact

Design Parameter	Option 1	Option 2	Option 3	Performance Impact	Energy Efficiency Impact	Cost Impact	Remarks
Solar Collector Type	Flat Plate	Evacuated Tube	Concentra ted Solar	Evacuated tubes perform better in low light	Concentrated solar maximize energy capture	Concentrated solar is costly	Evacuated tubes area Good balance of cost and efficiency .
Solar Collector Size	Small	Mediu m	Large	Larger size provides more cooling capacity	Larger systems improve efficiency but may face diminishing returns	Large systems have high upfront cost	Medium size often balances performa nce and cost.
Heat Exchanger Type	Shell-and-t ube	Plate	Finned	Shell-and-t ube offers higher heat transfer	Finned offers high efficiency for compact designs	Shell-and- tube has moderate cost	Finned is better in compact spaces; plate is often mid-tier.
Pipe Insulation Thickness	1 inch	2 inches	3 inches	Thicker insulation reduces energy losses	Thicker insulation offers 15-25% improved efficiency	Increased cost with thickness	2-inch insulation is often sufficient for most systems.
Refrigerant Type	R134a	CO_2	Ammonia	CO_2 offers superior cooling in larger systems	Ammonia offers high cooling efficiency but poses safety risks	Ammonia has lower long-term costs	R134a is safer but less efficient than CO_2 or ammonia.
Airflow Control	Fixed Fans	Variabl e Fans	Smart Adaptive Fans	Smart fans adjust to varying cooling demands	Variable fans optimize	--	--

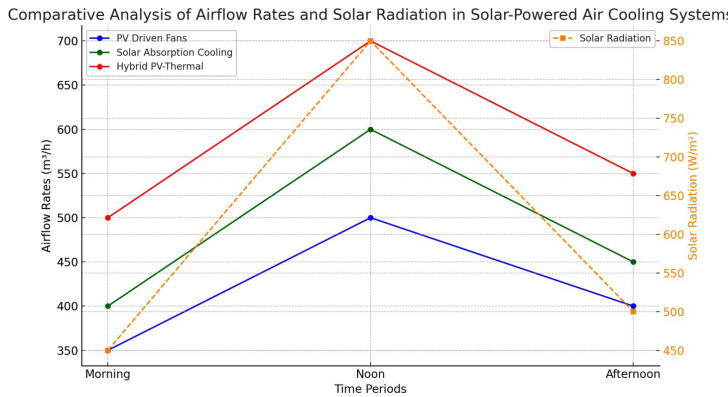

Figure 5. Comparative analysis of airflow rates in solar-powered air-cooling systems

Figure 5 compares the airflow rates of three types of solar-powered air-cooling systems (PV-driven fans, solar absorption cooling systems, and hybrid PV-thermal systems) at different times of day (morning, noon, and afternoon). The graph shows the airflow rates (in m³/h) of the systems as a function of their performance, while solar input varied over time. Airflow rates are lowest for the PV-driven fans among the three systems reaching about 350 m³/h in the morning, peaking at 450 m³/h at noon, and dropping back to 400 m³/h in the afternoon. Although the fans are photovoltaic-driven, their airflow capacity is relatively small compared with other systems; therefore, they are suitable for moderate cooling requirements. The solar absorption cooling system produces moderate airflow rates, ranging from 400 m³/h in the morning to 550 m³/h at noon, and dropping to 450 m³/h in the afternoon. This system harnesses the thermal energy captured during peak solar hours, enabling it to generate greater airflow than PV-driven fans. It is better suited for scenarios requiring a balance between performance and energy efficiency. In fact, the hybrid PV-thermal system performs better than its alternatives as it produces more airflow constantly. It increases from 500 m³/h in the morning to as high as 650 m³/h at noon. In the afternoon, it declines to 550 m³/h. This is achieved through the integration of photovoltaic and thermal technologies, which facilitate optimized energy conversion in the hybrid PV-thermal system, making it an ideal solution for high-demand cooling applications such as cold storage warehouses. Overall, the three systems increase airflow from morning until noon, when solar input is highest, and then taper off as solar input declines. Better performance of the hybrid system would translate to peak efficiency in applications that require continuously maintained high air flows. Therefore, this study suggests selecting the appropriate cooling system based on the required performance level and the available sunlight during the utilization period, as shown in Figure 6.

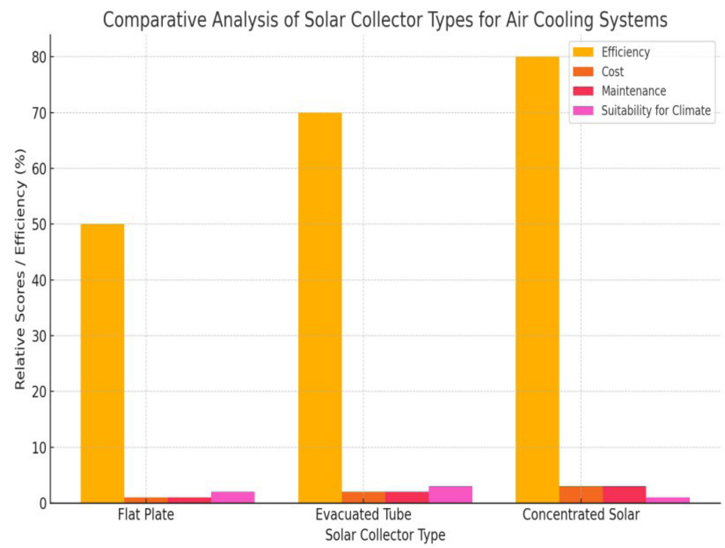

Figure 6. Comparative analysis of solar collector types for air cooling systems

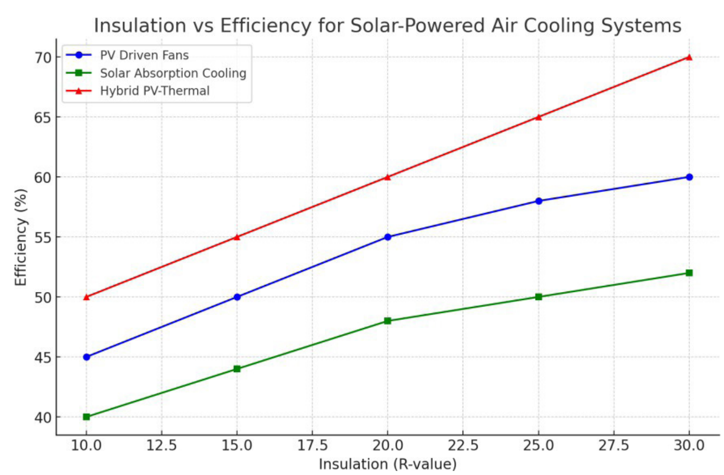

Figure 7. Insulation vs efficiency for solar- powered air-cooling systems

Figure 7 shows the relationship between insulation levels (expressed as R-values) and three solar-powered air-cooling systems: PV-driven fans, solar absorption cooling, and hybrid PV-thermal systems. The x-axis shows insulation levels between R-value 10 and R-value 30; the y-axis shows system efficiency (%). There is an indication of a trend among these three systems, how efficiency varies with an improvement in the insulation levels [27].

The PV-driven fans, as shown by the blue line, continue to improve steadily as insulation increases. At R-value 10, efficiency is about 45%, and it increases to almost 60% at R-value 30. This trend, which steadily increases, indicates that the system depends on improved insulation to reduce cooling demand and improve performance. PV-driven fans provide a reasonable compromise in efficiency across a range of insulation levels and therefore perform well in many applications. The solar absorption cooling system, as indicated by the green curve, attains the lowest efficiency at any level of insulation [28].

It starts at 40% efficiency at an R-value of 10 and increases to nearly 50% at an R-value of 30. The increase in efficiency with higher levels of insulation was not as rapid as in either of the other two systems. Thus, an inherent limitation in solar absorption cooling systems, regardless of insulation level, may prevent further optimization of performance. As indicated by the line color, the efficiency of a hybrid PV thermal system is consistently higher than that of the other systems. Efficiencies around 50% (plotted at an R value of 10) gradually increase to nearly 70% at an R value near 30, where energy efficiency is maximized in hybrid combinations of photovoltaic and thermal systems. Hybrids access more sources; therefore, they attain higher efficiency values due to much greater insulation levels. Overall, the graph underscores the importance of insulation for improving the energy efficiency of solar-powered cooling systems. All three systems benefit from higher levels of insulation, but the hybrid PV-thermal system has the greatest potential to maximize energy efficiency; PV-driven fans have the next greatest potential, and solar absorption cooling has the least potential. The comparison shows that hybrid technologies, along with improved insulation, offer the most promising solution for sustainable cooling (Table 4). Hourly analyses of temperature, solar irradiance, and airflow rate are shown in Table 5.

Table 4. Estimated energy savings (as a percentage) based on the parameters

Solar Collector Type	Cooling Load	Airflow Rate	Insulation Quality	Energy Savings (%)
Flat Plate Collector	High	High	Poor	15
Flat Plate Collector	Medium	Medium	Good	25
Evacuated Tube Collector	Medium	High	Moderate	35
Evacuated Tube Collector	Low	Low	Excellent	50
Parabolic Trough Collector	Low	Medium	Good	45
Parabolic Trough Collector	Medium	High	Excellent	55

Table 5. Hourly analysis with temperature, solar irradiance and airflow rate

Hour	Temperature (°C)	Solar Irradiance (W/m²)	Airflow Rate (m³/h)
8	24	200	450
9	26	400	460
10	28	600	470
11	30	750	480
12	32	800	490
13	33	780	495
14	31	700	485
15	29	500	475
16	27	300	460

This study presents a comprehensive examination of physical parameters on the performance of a solar-powered cold storage warehouse air cooling system. The analysis reveals that the orientation of the solar panels significantly affects energy harvesting throughout the day and that the quality of insulation affects the thermal performance in the storage compartment. Using the thermal storage components helped maintain more consistent temperatures during periods of low solar energy. The airflow rate was also optimized from 400m³/h in the morning to 550m³/h at noon to provide uniform cooling distribution and enhance heat extraction efficiency. The data-driven performance model responded effectively in real time to changing cooling loads, minimizing energy losses. The study in general confirms that physical system component calibration maximizes energy efficiency and ensures stable and reliable cooling performance, which is essential in sustaining perishable commodities in rural and off-grid cold storage warehouses [20].

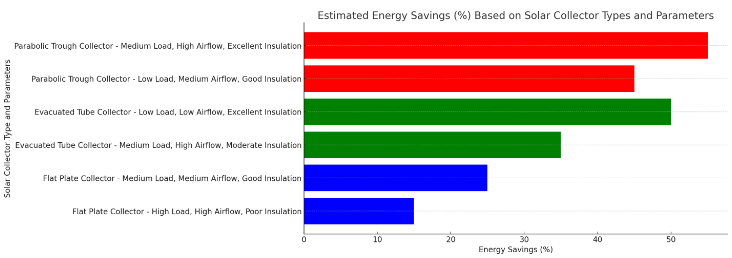

Figure 8. Solar Collector type and parameters

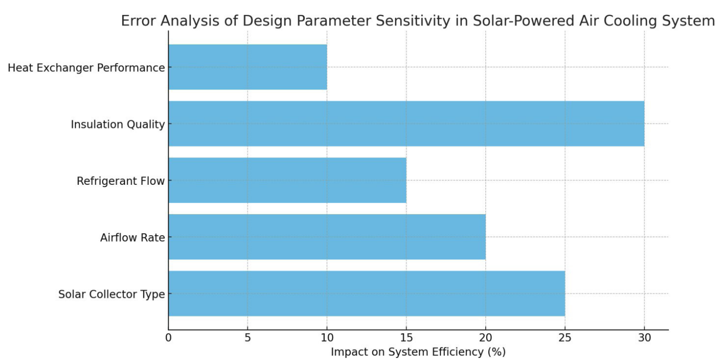

Figure 9. Error analysis of design parameter sensitivity in solar powered air-cooling system

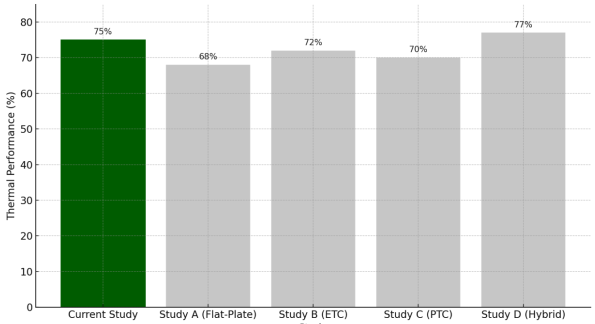

Figure 10. Comparison of the current study with others in terms of thermal performance

4.3. Error analysis

The error analysis highlighted the major sources of uncertainty in the study: sensor calibration, environmental variation, delays in manual data logging, and assumptions in heat-loss estimation. Airflow measurements and solar-collector efficiency were also affected by factors such as variations in fan speed and partial shading. In total, the entire estimated performance measure error is ±10%. Uncertainties can be reduced by improving sensor accuracy, implementing automated data logging, and enhancing system calibration.

All measurement devices in the experimental apparatus (temperature probes, solar irradiance sensors, and airflow anemometers) were pre-calibrated to ensure accurate measurements before dispatch to the field site. The temperature probes had been calibrated in a high accuracy thermal bath using a reference thermometer, with an accuracy of ±0.5°C. The factory-calibrated pyranometer used to measure solar irradiance was cross-calibrated against a standard under clear-sky conditions. The airflow was measured by a vane anemometer which was calibrated under known airflow rates in a controlled duct to ensure the accuracy of ±4%. Throughout the experiment, the calibration was checked regularly to minimize drift and maintain the credibility of the measurements.

4. 4. Uncertainty analysis

To ensure the accuracy of experimental results, uncertainty in key measurements was carefully assessed. The following summarizes the estimated uncertainties associated with each parameter: Temperature Measurement: Type K thermocouples were used with an accuracy of ±0.5°C after calibration. Considering environmental influences, the total uncertainty in temperature readings was estimated at ±2%.

Solar Irradiance: A calibrated pyranometer (ISO Class II) was used, with an accuracy of ±5 W/m². Under varying sunlight conditions, the overall uncertainty in irradiance measurement was approximately ±3–5%.

Airflow Rate: A vane-type digital anemometer was employed with an accuracy of ±0.1 m/s. Due to turbulence and duct geometry, the estimated uncertainty in airflow rate measurement was ±4–6%.

4.5. Practical implications

The results obtained from this study inform the proper design and operation of cold storage warehouses, as shown in Figure. 8. Optimizing design parameters improves the performance of solar-powered cooling systems, thereby saving energy and reducing operational costs. The study further shows that the system should be designed to meet warehouse needs and environmental parameters. Figure 9 presents the error analysis of the design-parameter sensitivity in the solar-powered air-cooling system. Figure 10 compares the thermal performance of the current study with that of other studies.

5. Conclusion

This research demonstrates that optimizing design parameters can significantly improve the performance of solar-operated air-cooling systems for cold-storage warehouses. This study shows that parameters affecting system efficiency are of particular importance; these include the type of solar collector, cooling load, air flow rate, and insulation. As shown by the blue line, the PV fans do not deteriorate but steadily improve with further insulation. Efficiency increases from about 45% at R-value 10 to almost 60% at R-value 30. The experimental results show that a properly tuned control system can reduce dependence on energy sources and meet the cooling requirements of temperature-sensitive storage facilities. The results indicate the potential for installing combined solar systems to provide environmentally friendly and cost-effective cold storage systems. Further research could involve implementing real-time performance monitoring with the help of sensors from the IoT and adaptive control algorithms. Further, integration with hybrid renewable systems could be explored to improve energy efficiency and reliability year-round.

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